ALUMINIUM-STEEL ENERGY DISSIPATORS FOR PASSIVE PROTECTION OF STRUCTURES

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ABSTRACT :

In the present paper, the design optimization and the buckling analysis of an aluminium-steel device for the seismic protection of structures are presented. Moreover, it is detailed discussed the dynamical response of a 3D two-storey steel frame, equipped with the proposed device and subjected to 14 natural earthquakes, which are compatible with the response spectra provided by Eurocode 8.

KEYWORDS: Passive control, yielding-based device, design optimization, non-linear dynamical analysis.

1. INTRODUCTION

Energy dissipators are a widely spread category of devices commonly used for reducing the response to seismic inputs in civil structures. Among these, metallic yielding-based devices provide a reduction of the energy entering the structure, thanks to the hysteresis of the material when the yielding limit is exceeded. In particular, steel shear panels are examples of metallic yielding-based devices, which dissipate energy under a shear behaviour.

Generally, such dampers are known to possess large energy-dissipation capacity; moreover, they increase the stiffness of the structure and reduce the interstory drifts by concentrating the damage in the device. In this way, the protection of the structure is extended to the protection of the non-structural elements too. In addition, shear panels can be easily installed in the frame and substituted after a seismic event. Finally, they are cost-effective like all the metallic yielding-based devices. As disadvantages for these kind of Energy Dissipating Devices, the dissipative capacity is activated only after they sustain inelastic excursions; as a consequence, the devices are ineffective for vibrations smaller than the yielding interstory drift.

To reduce the yielding interstory drift, low-yield-steel (LYS) has been proposed as dissipating material for shear-link devices (Nakashima *et al.*, 1994). As disadvantages, low yield steel is not easily available in the world market, and is quite expensive. In order to overcome these limits, some authors (Foti & Diaferio, 1999) have proposed the use of aluminium alloy. In fact, aluminium alloy is characterized by a low yielding force - lower than the LYS one -, a wide plastic range and a Young's modulus lower than the steel one.

In Rai & Wallace (1998), Foti & Diaferio (1999), Rai (2002), hysteretic devices realized with ordinary aluminium alloys are studied and the results of numerical and experimental investigations shown. In Foti & Nobile (2000), Foti & Nobile (2001), Foti & Zambrano (2004), by performing dynamic characterization tests and shaking-table tests on aluminium devices, the instability phenomena and specific problems deriving from the damage localized at the connections of the device to the structure are discussed. Other authors (De Matteis *et al.*, 2003; De Matteis *et al.*, 2007) have proposed the use of pure aluminium for dissipative devices.

In Diaferio, Foti & Nobile (2008), the optimal design has been applied to an aluminium-steel shear panel, by using an FE model of the dissipating device.

In the present paper, the non-linear dynamical response of a 3D two-storey steel frame equipped with a new aluminium–steel shear panel is proposed. The device is similar to the panel designed in Diaferio, Foti & Nobile (2008), but with a better behavior to the shear buckling and a better global performance under different accelerograms.

2. ALUMINIUM- STEEL SHEAR PANEL

Shear panels could dissipate a large amount of energy when two conditions are satisfied: the first is that inelastic excursions are activated in correspondence of a low yielding limit - that could guarantee the protection of the structure even in the range of small vibrations -, the second is that they show a wide plastic range. These two peculiarities give contrasting requirements: the reduction of the yielding limit implies a reduction of the dimensions of the device and, on the other side, the request of a wide plastic range needs an increment of some dimensions of the device, in order to increase the shear buckling threshold, and, as a consequence, to avoid the possibility of an out-of-plane instability of the device.
On the basis of the above mentioned considerations, the proposed device has been designed as composed by three plates: the central plate, preferentially devoted to the energy dissipation, and two more external plates, with the main aim of reducing the possibility of out-of-plane instability (Figure 1). In particular, Fe360 steel has been chosen for the external plates, and 1000 aluminium alloy has been chosen for the web of the device. The choice of the aluminium alloy is due to its low yielding stress and its wide plastic range. In Table 1 the mechanical properties of the two materials are described.

Table 1 Steel and aluminium mechanical properties

	Material properties	**Fe360**	**1000 Al series**
σ_y	yielding stress [N/mm^2]	235	30
σ_R	ultimate tensile strength [N/mm^2]	360	90
A	elengation to failure [%]	26	40
E	Young's modulus [N/mm^2]	206000	70000
H	Plastic modulus [N/mm^2]	20000	5000

The steel plates present some rectangular openings where the central aluminium plate partly emerges into the steel; in this way, steel openings represent an obstacle to slip phenomena. Moreover, bolts have been considered to guarantee a better connection between the plates. In order to increase the buckling threshold, the steel plates are oriented with their higher inertia in the direction of the out-of-plane instability. A typical configuration of the panel is shown in Figure 1.

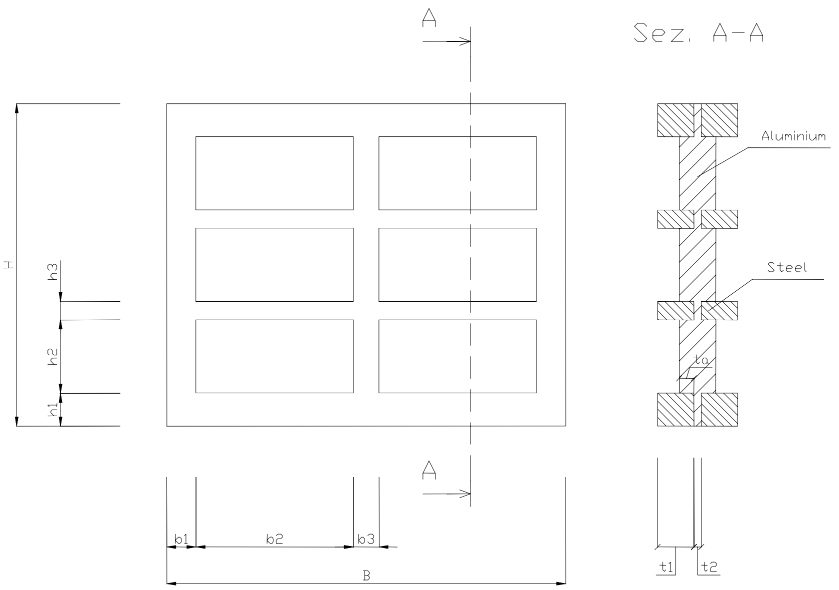


Figure 1 Geometrical parameters of the aluminium device.

The shear panel has been proposed within the Research Project No. 7 of 2005-2008 ReLuis Project (Serino *et*

al. 2007, Gattulli *et al.*, 2007; Ponzo *et al.* 2007), whose scope is to conduct analytical and experimental investigations on seismic control techniques.
An optimisation analysis has been carried out to define the geometrical configuration of the device by means of the Ansys software. The panel has been modelled using 20-nodes solid elements SOLID90 having a parabolic shape function. The mechanical behaviours of steel and aluminium have been described by bi-linear laws, whose parameters were defined in accordance with the properties shown in Table 1.
Moreover, the shear panel has been modelled as fixed at the base and able to move only in the horizontal direction at the upper bound. The assumed constraints have been adopted in order to simplify the installation of the device in the structure. In particular, the device could be welded or connected with some bolts at the base and at the upper bound.
The geometrical shapes and dimensions of the aluminium-steel shear panel have been determined by imposing a maximum horizontal displacement equal to 4 mm, that is 0.2% of the interstory height of a steel frame described in chapter 3, in which the proposed device will be installed and subjected to shaking-table tests (Ponzo *et al.*, 2007).
An optimization procedure for an FE model of the device has been applied. It essentially consists of the following steps:

- individuation of the objective function to be maximized;
- declaration of the parameters that define the geometry of the device;
- definition of the variability ranges of the parameters, in order to exclude unrealistic solutions;
- individuation of constraint functions.

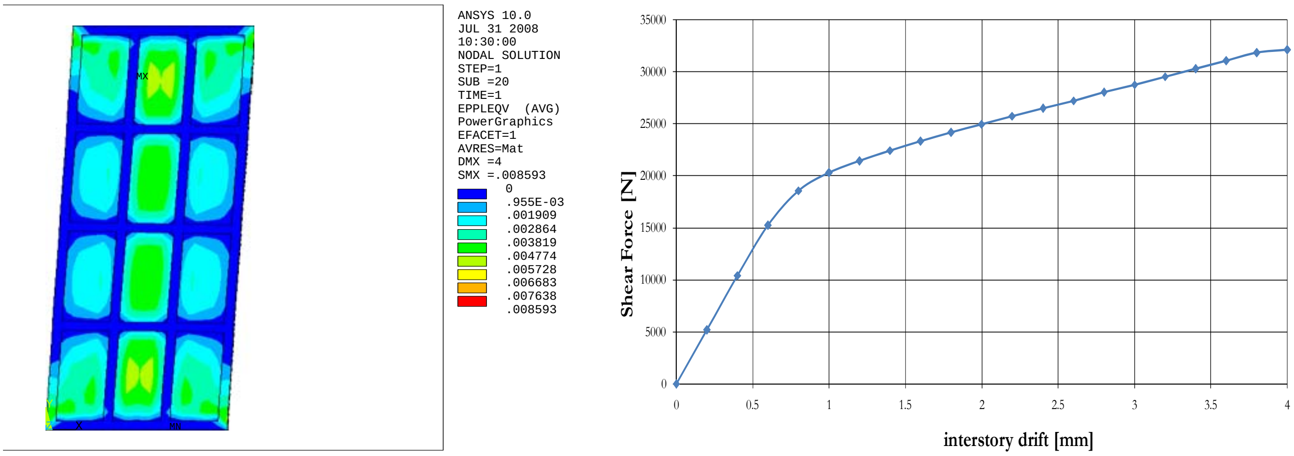
The objective function to maximize has been chosen equal to the plastic strain energy in the aluminium plate.
In Figure 1, the main geometrical parameters needed to define the device configuration are shown.
The optimal design has been performed by assuming the ranges for the parameters of the aluminium-steel device and the starting configuration contained in Table 2.

Table 2. Starting configuration of the aluminium-steel device and variability ranges of the parameters.

Geometrical Parameters		Starting Configuration	Variability range
n_x	horizontal openings	6	2-6
n_y	vertical openings	4	1-4
b_1	lateral steel stiffener width [mm]	20	5-20
b_2	aluminium opening width [mm]	60	20-200
b_3	internal steel stiffener width [mm]	20	5-20
h_1	external steel stiffener height [mm]	20	5-20
h_2	aluminium opening height [mm]	70	20-400
h_3	internal steel stiffener height [mm]	20	5-20
t_1	steel plate thickness [mm]	1	1-10
t_2	aluminium plate thickness [mm]	3	1-4
t_a	aluminium opening projection [mm] (fig.1)	2.5	1-4

Finally, correct formulation of the optimization procedure requires the following different constraint functions: maximum stress = 90 MPa; panel height = 380-450 mm; panel width = 150-600 mm; such constraints have been defined on the basis of geometrical considerations on the installation of the devices in the two-story steel frame described in chapter 3.
The optimization routine has been performed by fixing *a priori* many configurations of the device, each one characterised by certain fixed numbers of the vertical and horizontal openings. The final results would be an optimized solution for each configuration; among them it would be easy to find the best configuration.
In Diaferio, Foti & Nobile (2008) the optimization analysis has been performed by assuming that the aluminium plate is thicker than the steel one; on the contrary, in the present paper the optimization procedure has been performed to evaluate the dimensions of an aluminium-steel device characterized by steel plates with thickness higher than the aluminium plate. In fact, the analysis has shown that, even in the case of devices with the same yielding force, the dissipater with a thickness of the steel plates higher than the aluminium plate shows

an almost uniform plasticization of the aluminium plate (Figure 2a): this could improve the dissipative capacities of the device. Thus, in the present paper, the dynamical analysis has been performed adopting the last solution and the dimensions reported in Figure 2. In particular, the Von Mises strain and the constitutive law of the proposed shear panel are shown.



(a) (b)

Figure 2 Aluminium - steel device with 12 windows (nx 3 and ny 4) and b_1= 8mm, b_2=40mm, b_3=8mm, h_1=10mm, h_2=100mm, h_3=10mm, t_1=5mm, t_2=3mm, t_a=2mm: a) Von Mises strain; b) constitutive law

A buckling analysis of the proposed device has been performed in order to evaluate the shear threshold that activates the out-of-plane instability. The results show that the instability of the aluminium-steel device occurs at an interstory drift equal to 3.928mm (Figure 3). As a consequence, the device is able to guarantee a wide plastic range and an high dissipative capacity.

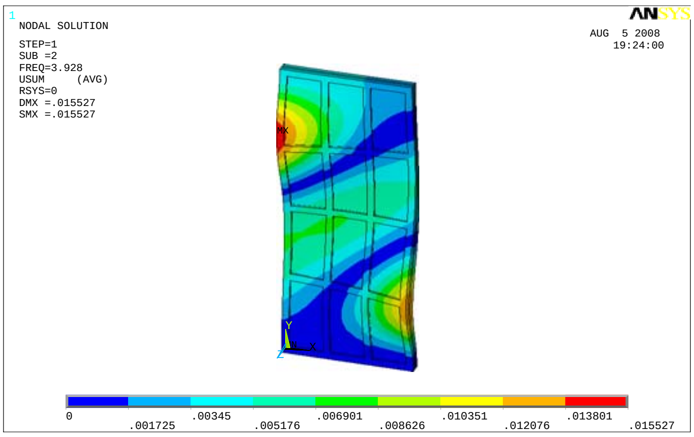


Figure 3 Buckling analysis of the aluminium - steel device with 12 windows (nx 3and ny 4) and b_1= 8mm, b_2=40mm, b_3=8mm, h_1=10mm, h_2=100mm, h_3=10mm, t_1=5mm, t_2=3mm, t_a=2mm.

3. TEST SPECIMEN

The proposed device has been designed to protect a 3D two-storey steel frame during shaking-table tests (Figure 4), that will be performed at the Structural Engineering Laboratory of the University of Basilicata in Potenza (Serino *et al.* 2007, Ponzo *et. al.* 2007). The specimen represents a 2:3 scaled steel frame; it has 3m x 4m plan size and presents four HEB140 columns placed at the corners and IPE180 beams welded to the columns. The storey height is about 2 m, and the columns emerges of 0.5m from the upper floor (Figure 4).

The two floors are realized with concrete slabs supported by a A55/P600 coffer steel section with a thickness of 0.8mm. Moreover, HEA160 horizontal bracings are mounted in the plane of the ground floor. The frame is also equipped with chevron type bracings made of HEA100 mounted in the vertical planes (Figure 4c) and good to install the seismic protection devices. In detail, the proposed devices will be bolted at the base to the chevron bracings and at the upper bound of the beam. In this way, all rotations at the boundaries could be neglected.

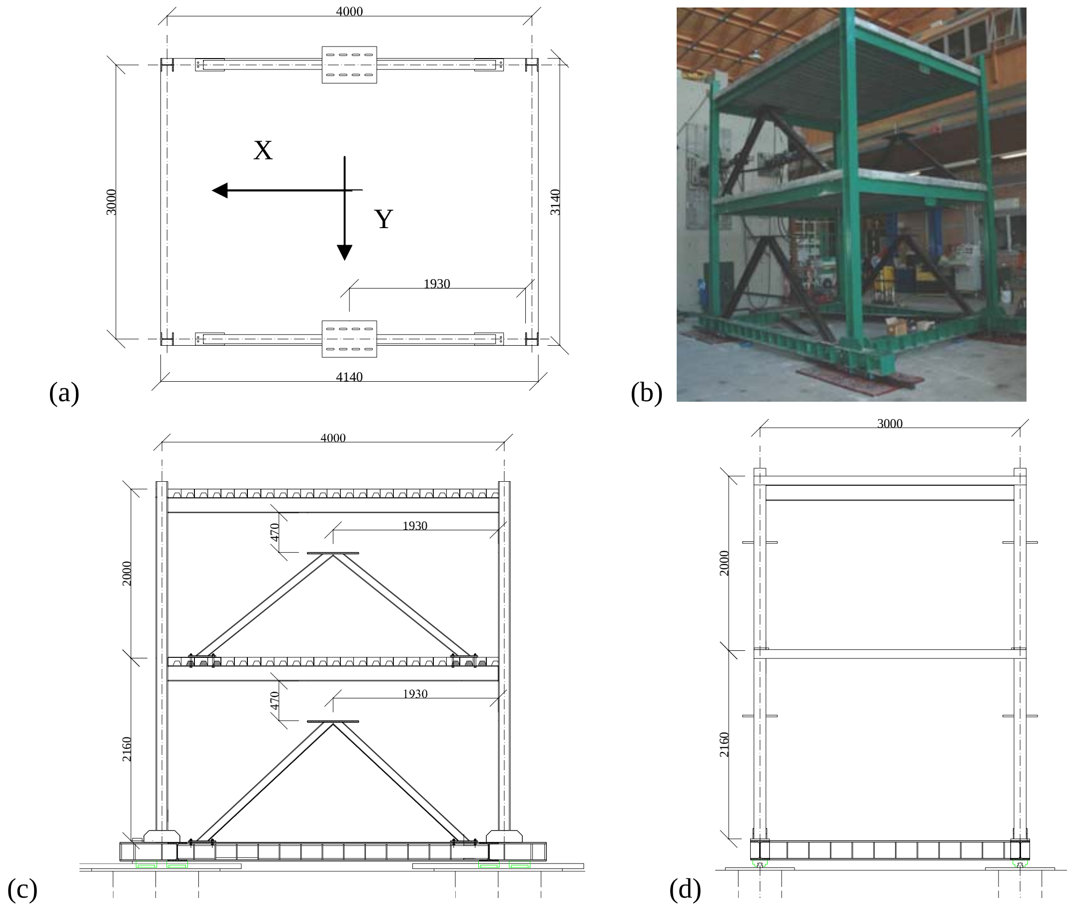
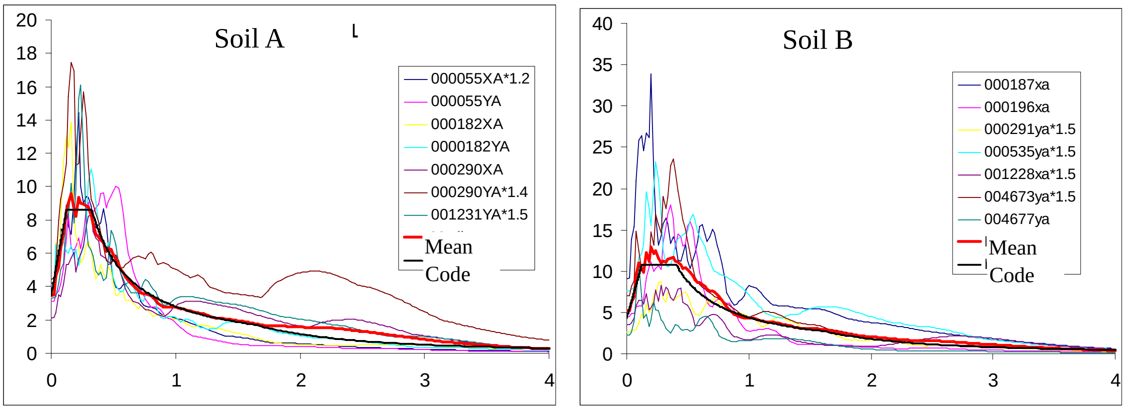


Figure 4 2:3 scaled steel frame built at the Structural Engineering Laboratory of the University of Basilicata in Potenza, Italy (Gattulli *et al*, 2007): a) plan view, b) 3D view, c) vertical plane XZ, d) vertical plane YZ.

4. NON-LINEAR DYNAMICAL ANALYSIS

The aim of the current non-linear dynamical analysis is to investigate the beneficial effects of the proposed aluminium – steel device for enhancing the seismic performance of the above mentioned 3D steel frame. Numerical results have been obtained by means of SAP 2000 Nonlinear ®.
The analysis has been performed considering the installation of four aluminium-steel shear panels in the vertical planes between the chevron bracings and the frame (Figure 4c), and by modeling the devices as nonlinear links with the constitutive law of Figure 2b. The non-linear dynamical analysis has been performed subjecting the steel frame with (*protected frame*) and without (*bare frame*) aluminium-steel dissipators to 14 natural earthquakes, acting in the X direction. In particular, 7 earthquakes (see Figure 5a) are compatible with the response spectrum provided by Eurocode 8 for type A soil in seismic zone 1, and they are characterized by a seismic intensity equal to 0.35g; the other 7 earthquakes are compatible with the response spectrum provided by Eurocode 8 for type BCE soils in seismic zone 1 and they are characterized by a seismic intensity equal to 0.42g (Serino *et al.* 2007, Ponzo *et al.* 2007) (see Figure 5b).



(a) (b)

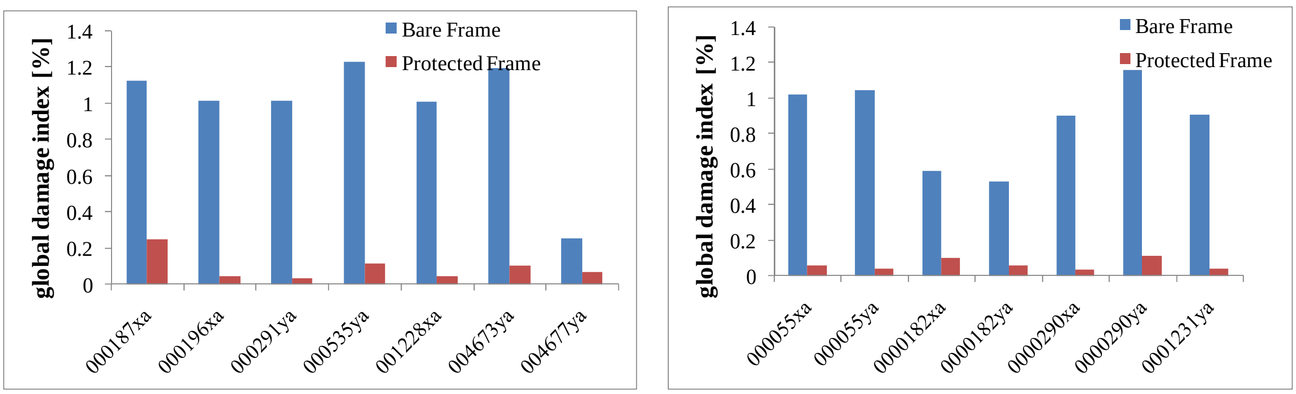
Figure 5 a) Response spectrum of considered natural earthquakes compatible with Eurocode8 for type A soil in seismic zone 1, PGA=0.35g; b) Response spectrum of considered natural earthquakes compatible with Eurocode8 for type *BCE* soils in seismic zone 1, PGA=0.42g (Ponzo *et al.* (2007))

In Table 3 the modal frequencies of the bare and protected frames are shown. As a consequence of the installation of the aluminium-steel dissipaters, the frequencies of the bending modes in the X direction – i.e. the effective direction of the devices – and of the torsional modes significantly increase.

Table 3 Modal frequencies of the bare frame and the frame protected with aluminium shear panels

Mode	**Bare frame frequency [Hz]**	**Protected frame frequency [Hz]**
I bending Y direction	2.86	2.91
I bending X direction	3.56	10.64
I torsion	5.79	12.46
II bending Y direction	9.18	9.16
II bending X direction	12.53	29.14
II torsion	18.56	34.21

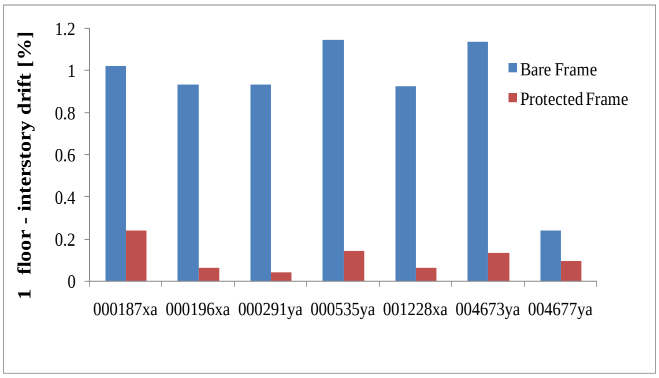
The global damage index – defined as the ratio of the top displacement on the total height of the frame – is shown in Figure 6. The results show that the response of the protected frame is three or four times smaller than the one of the bare frame, and, in all the examined cases, no plasticization occurs in the frame.



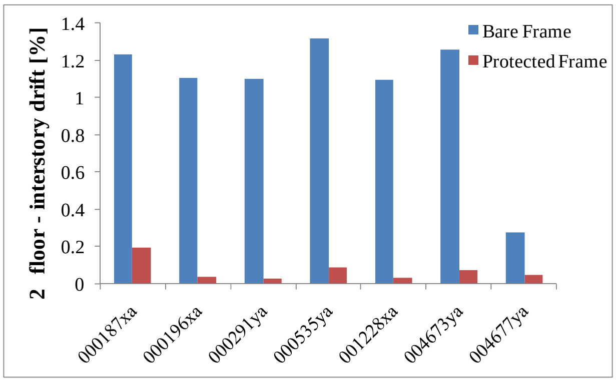
(a) (b)

Figure 6: Global damage index for earthquakes compatible with Eurocode8: a) for type *BCE* soils in seismic zone 1, PGA=0.42g; b) for type A soil in seismic zone 1, PGA=0.35g.

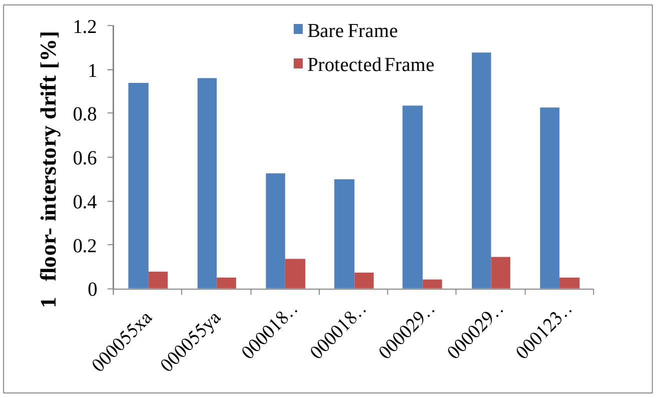
In order to emphasize the effects of aluminium-steel dampers, the maximum interstory drift index has been evaluated for each one of the 14 earthquakes. The above mentioned index is defined as the ratio of the maximum interstory drift on the story height. In Figure 7 the indexes evaluated at each floor are represented. It is shown that for all the examined cases, the response of the protected frame satisfy the recommendation that the index must not exceed the limit of the 0.5%, that is the security limit estimated with reference to the first plasticization of the frame (Ponzo *et al*. 2007).



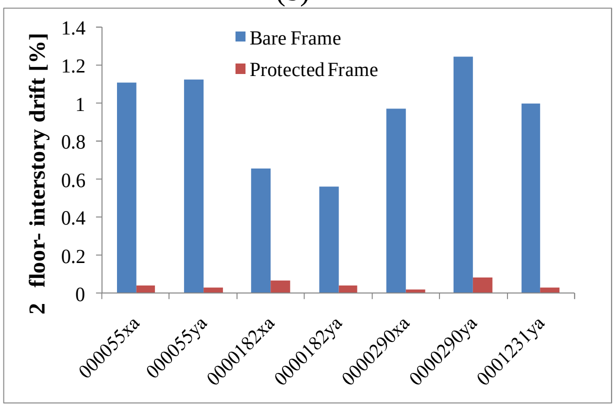
(a)



(b)



(c)



(d)

Figure 7 Maximum interstory drift index: earthquakes compatible with Eurocode8 for type *BCE* soils in seismic zone 1, PGA=0.42g a) 1° floor and b) 2° floor; earthquakes compatible with Eurocode8 for type A soil in seismic zone 1, PGA=0.35g c) 1° floor and d) 2° floor.

5. CONCLUSION

The aim of this study is to achieve a better knowledge of the effectiveness of an aluminium-steel device for seismic protection of structures. The proposed dissipater has been numerically tested on a steel frame subjected to seven natural earthquakes, which are compatible with the response spectrum provided by Eurocode 8 for type A soil in seismic zone 1 (PGA=0.35g), and to seven more natural earthquakes, compatible with the response spectrum provided by Eurocode 8 for type BCE soils in seismic zone 1 (PGA=0.42g). In this way, the non-linear dynamical analysis has been performed by taking into account different characteristics of soil and seismic intensity. In all the examined cases the results show that the proposed device is able to avoid the plasticization in the frame and to guarantee a high protection of the structure.

6. ACKNOWLEDGEMENTS

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